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CERENKOV-SCINTILLATION COUNTER MEASUREMENTS OF THE LIGHT, MEDIUM, AND HEAVY NUCLEI IN THE PRIMARY COSMIC RADIATION FROM SUNSPOT MINIMUM TO SUNSPOT MAXIMUM

F. B. McDonald and W. R. Webber

Goddard Space Flight Center
Greenbelt, Maryland

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

The intensity and rigidity spectra of Be, B, C, N, and O have been measured on a series of three Skyhook balloon flights using a Cerenkov-scintillation detector combination. The flights occurred at times close to solar minimum and maximum. The energy and charge resolution is comparable with that obtained by the latest emulsion techniques. It is observed that the light and medium nuclei display the same relative rigidity spectra throughout the solar cycle as the protons and α particles. This conclusion is valid only in the region studied ($E > 400$ Mev/nucleon), and we may well expect striking variations for heavy primaries of low energy. The measured ratio of light to medium nuclei at the top of the atmosphere was 0.36 ± 0.06. This was not observed to vary appreciably over the solar cycle.

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INTRODUCTION

Measurements on primary cosmic-ray nuclei heavier than α particles have provided much information helpful in understanding the problems relating to the acceleration and the propagation of primary cosmic rays to the earth. Two characteristic features of these heavier nuclei are utilized in interpreting these measurements.

1. Because of their fragile structure, which can be easily destroyed in nuclear interactions at cosmic-ray energies, heavier nuclei cannot be created from lighter elements once they are ejected from the source into interstellar space. Thus any conceivable process the primary cosmic radiation might undergo in interstellar space takes place in the direction from heavier to lighter elements. Experimentally this feature is reflected in the study of the relative abundance of each of the heavier nuclei and, in particular, the relative abundance of the so-called light nuclei (Li, Be, B), which are commonly believed to be absent in the cosmic-ray source regions. A knowledge of these relative abundances, together with the fragmentation parameters of these nuclei in the interstellar medium, can lead to definite limitations on acceleration and propagation processes of the primary cosmic radiation.

2. The rate of energy loss in the passage through interstellar material is greater for the heavier nuclei, being proportional to the Z^2/β^2 of the particle. The effect of this ionization loss will be most pronounced at the low-energy end of the spectrum. Experimentally this feature should be revealed by a comparison of the differential energy spectra of the various charges, particularly at energies where β is appreciably less than 1. Thus a knowledge of the shape of the differential spectra for the various charges can place further limitations on cosmic-ray acceleration processes and on the travel of cosmic rays in the interstellar medium.

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†Now at the School of Physics, University of Minnesota, Minneapolis, Minnesota.

Recent progress in balloon techniques and the practicality of studies in satellites have opened the possibility for further advances in the study of these heavier nuclei. Particularly, it is now possible to study the energy spectra of the individual nuclei or groups of nuclei in much the same manner as proton and α-particle spectra have been studied for a number of years. The additional information to be derived from such studies, as is noted above, opens up a new dimension for attacking the problems outstanding in this field.

A number of preliminary investigations of the low-energy portion of the spectra of the heavier nuclei ($Z \geqq 6$) have recently been made by means of emulsion techniques. They have led to a somewhat confused picture however. For example, the results reported by Fichtel (Reference 1) and Evans (Reference 2) tend to suggest that the differential spectra of the light L, medium M ($6 \leqq Z \leqq 9$), and heavy H ($Z \geqq 10$) nuclei are similar to those for protons and α particles (when the intensities are expressed in particles/m^2-ster-sec-Bv). Aizu et al., from results of much greater statistical significance (References 3 and 4), find an anomalous spectrum for the L nuclei. Finally, Tamai (Reference 5) reports systematically different spectra for all charge groups, the peak in the differential spectrum occurring at higher energies for the particles of higher Z.

It should be pointed out that all these measurements were made at times when the solar modulation of cosmic rays was appreciable and variable, that is, at times near *sunspot maximum*. The effect of this modulation on the heavier nuclei has not been directly measured on separate occasions over the sunspot cycle but has been inferred from comparison of these spectra with those of protons and α particles reported at similar times. Since it has been established that the solar modulation for protons and α particles is similar when expressed in terms of changes in the rigidity spectra of these particles (References 6, 7, and 8), we should expect this rigidity dependence to hold for the heavier nuclei as well because of their identical Z/A.

In actual fact, because of the solar modulation effects, which are certainly large and not yet known with sufficient accuracy, it is necessary to measure the spectra of the heavier nuclei at times near *sunspot minimum* when solar modulation effects are probably small, or at least do not fluctuate rapidly—that is, if we hope to obtain useful information on the acceleration and propagation of the primary cosmic radiation outside of the solar system by these measurements.

In the light of the above situation, and to investigate the ability of counter techniques to examine the charge and energy spectra characteristics of the heavy nuclei, it seems worthwhile to report here the results from a series of three flights using Cerenkov-scintillation counters to measure the energy spectra of charges with $3 \leqq Z \leqq 10$. The data were obtained in conjunction with a series of more than twenty flights to measure the proton and α-particle spectra during the period 1954 to 1959 (References 6, 7, 8, 9, and 10). The three flights cover the period from sunspot minimum to sunspot maximum. The flight near sunspot minimum provides the only spectral measurements of the heavier nuclei yet reported and as such will be used in deducing certain new limitations on the propagation and acceleration of the galactic radiation. The measurements of the cumulative effects of the solar modulation on the heavier nuclei will be used to extend the conclusions reached earlier for the effects of this modulation on protons and α particles.

DESCRIPTION OF DETECTORS USED

The detector used in the measurements reported here is identical to that used to measure protons and α particles; the detector and recording system have been described in detail previously (Reference 9). Briefly, the detector is a three-element telescope consisting of an NaI crystal scintillation counter, a Lucite Cerenkov counter, and a tray of Geiger counters (except for third flight; see below). The scintillation crystal and the Geiger counter tray are the defining elements of the telescope. For each particle that traverses these elements, the outputs from the Cerenkov counter and the scintillation counter are recorded. The relation between the measured outputs from the Cerenkov counter ($I_c \approx Z^2$) $(1 - 1/\beta^2 n^2)$ and the scintillation counter ($I_s \approx Z^2/\beta^2$) should uniquely determine the charge and velocity of the particle in question. In actual practice it is possible to measure the spectra of the heavier nuclei in the range of $\approx$ 250 to 1500 Mev/nucleon. The low-energy limit, which is Z-dependent, is determined by the ionization cutoff introduced by the material in the detector and the atmosphere above, and also by general background pulses in this region of zero Cerenkov output. A system of guard counters is used to detect and minimize such background counts, usually due to interactions and knock-on electrons occurring in the detector and particularly in the detecting elements themselves.

The instrumental calibrations are a very important aspect of this experiment. It is necessary first to identify the pulse height distributions of the relativistic particles of each charge and then to relate these positions to the output pulses from the lower energy particles in order to ascertain their energy. The response and linearity of the electronic system were checked carefully before and after each flight by introducing simulated photomultiplier pulses whose amplitude could be controlled accurately as multiples of Z^2, where $Z = 1$ amplitude was established to within 5 percent by tests using μ mesons at sea level.

In practice the ground calibration is confirmed by noting the relative positions of the peaks of the ionization and Cerenkov distributions of relativistic α particles and carbon nuclei at balloon altitudes. The centers of these distributions corresponding to $(I_s)_{min}$ and $(I_c)_{min}$ can be determined to an accuracy of $\pm$10 percent. These positions agree to within the experimental error with those expected from a linear system on the basis of the sea-level calibration. The positions $(I_s)_{min}$ and $(I_c)_{min}$ for the other charge components can be determined with less accuracy but do not indicate any nonlinearities in the system. From this we conclude that saturation effects are small in NaI crystals for relativistic particles with $Z \leqq 10$.

The energy spectra of the heavier nuclei are determined by using the theoretical variations of I_s and I_c with velocity. It is estimated that energies in the range 250-1500 Mev/nucleon can be measured to an accuracy of $\approx$ 10 percent or less for particles with $4 \leqq Z \leqq 10$. The observed counts appear to fall along the predicted curves for these lower energy particles, and there is no evidence for a systematic distortion of the energy calibration.

The third flight reported here was made with a somewhat different detector: A second NaI scintillation crystal was used in place of the Geiger counter tray. The two scintillation crystals were the defining elements of the telescope, and for each particle three outputs (two scintillation and one

Cerenkov) were recorded—giving, in effect, a double-scintillation - Cerenkov detector. A schematic drawing of this detector is shown in Figure 1. Its characteristic features are generally similar to the earlier one, but the replacing of the Geiger counter tray by the second scintillation crystal led to certain notable improvements: (1) The second scintillator provided a self-consistent check on the charge and energy of the particles as determined from the relative outputs of the Cerenkov counter and the other scintillation crystal; comparison of the outputs of the two scintillation crystals gave an additional parameter to check the change and energy, namely, a measurement of the rate of energy loss of the particles at two different points on the trajectory. (2) The second scintillator also reduced the problem of background counts to negligible proportions. Since most of these "confusion" counts were due to interactions or knock-on electrons produced in the material of the detector itself, a greater degree of selection for these local events could be made by comparing the two scintillation outputs that reflected ionization loss conditions upon entrance and exit from the detecting system. Only events consistent with single particles traversing the system were used. The extra scintillator acted as a "guard" system so efficiently that it was possible to dispense with the "guard" counters in the later system.

EXPERIMENTAL RESULTS

The data on which this report is based, as noted before, come from three balloon flights of the Cerenkov-scintillation or Cerenkov - double-scintillation detector (see Table 1). As a measure of the cumulative effects of solar activity at the time of the flights the average Mt. Washington neutron monitor hourly scaled counting rates are given for the times the detectors were at peak altitude. The peak hourly scaled rate at Mt. Washington during the period of actual sunspot minimum in 1954 was ≈ 2500; thus conditions on August 17, 1956, indicate a solar modulation effect of ≈ 4 percent as recorded by a high-latitude neutron monitor. On March 20, 1956, the intensity was recovering from a Forbush decrease, and the total solar modulation was ≈ 12 percent. Finally on August 1, 1958, the cumulative solar modulation was ≈ 22 percent, which represents almost the full magnitude of the solar modulation effects as recorded by such a monitor (Reference 11).

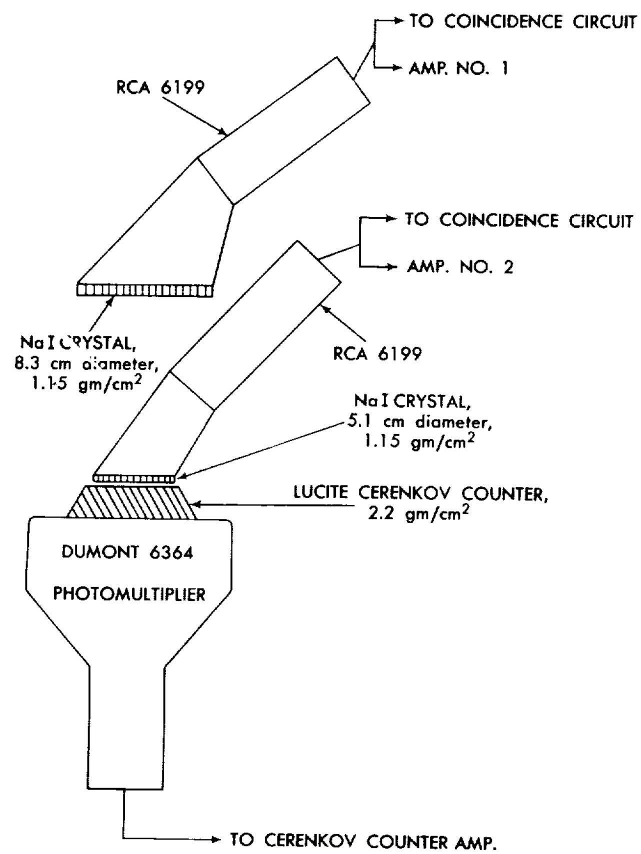

Figure 1—Double-scintillation - Cerenkov telescope. For an event, the pulse height of each of the three counters is recorded.

Figures 2, 3, and 4 show the two-dimensional plots of all the counts recorded on

Table 1

Details of Balloon Flights.

Flight Data	Flight Number		
	6	7	A
Date	March 20, 1956	August 17, 1956	August 1, 1958
Altitude (average)	6.8 gm/cm^2	5.3 gm/cm^2	5.0 gm/cm^2
Location	Iowa City, Iowa	Minneapolis, Minn.	Moberly, Mo.
Geomagnetic threshold during flight*	1.7 - 1.2 Bv	1.2 ± 0.1 Bv	2.5 ± 0.1 Bv
Hours of data	6	4	6
Geometric factor	7.2 ster-cm^2	7.2 ster-cm^2	6.4 ster-cm^2
Amount of absorber in detector	11.4 ± 2 gm/cm^2 (unit 1)	11.4 ± 2 gm/cm^2 (unit 1)	8 ± 2 gm/cm^2 (unit 2)
Mt. Washington neutron intensity at time of flight (scaled counts per 2-hr interval)†	2205	2415	1975

*After Quenby and Webber (Reference 12).

†Courtesy of Prof. J. A. Lockwood, University of New Hampshire.

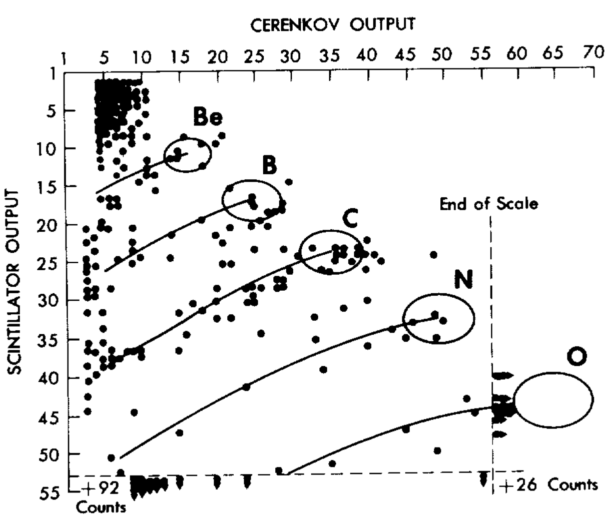

Figure 2—Two-dimensional plot of Cerenkov light output versus ionization loss for counts recorded on flight 6, March 20, 1955. The complete absence of counts in the region of high Cerenkov pulse height and the small scintillator output indicate the lack of background in the fast particle region. The lithium region is obscured by background, and there are probably background counts in the region below 400 Mev/nucleon.

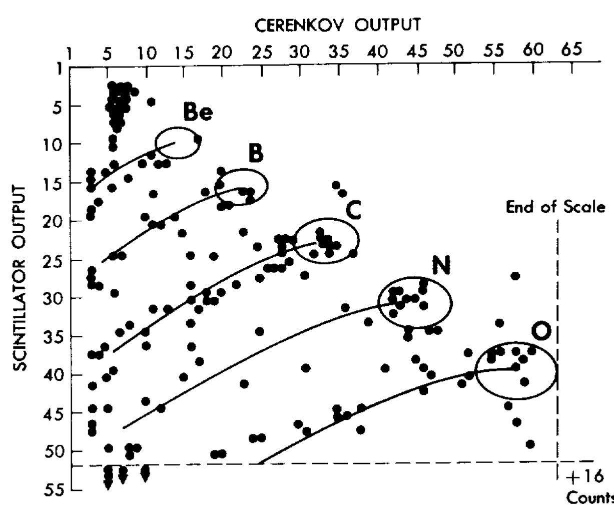

Figure 3—Two-dimensional plot of Cerenkov light output versus ionization loss for counts recorded on flight 7, August 17, 1956. As in Figure 2, the curves indicate the theoretically expected distribution. The separation between boron and carbon is particularly good for both flights 6 and 7.

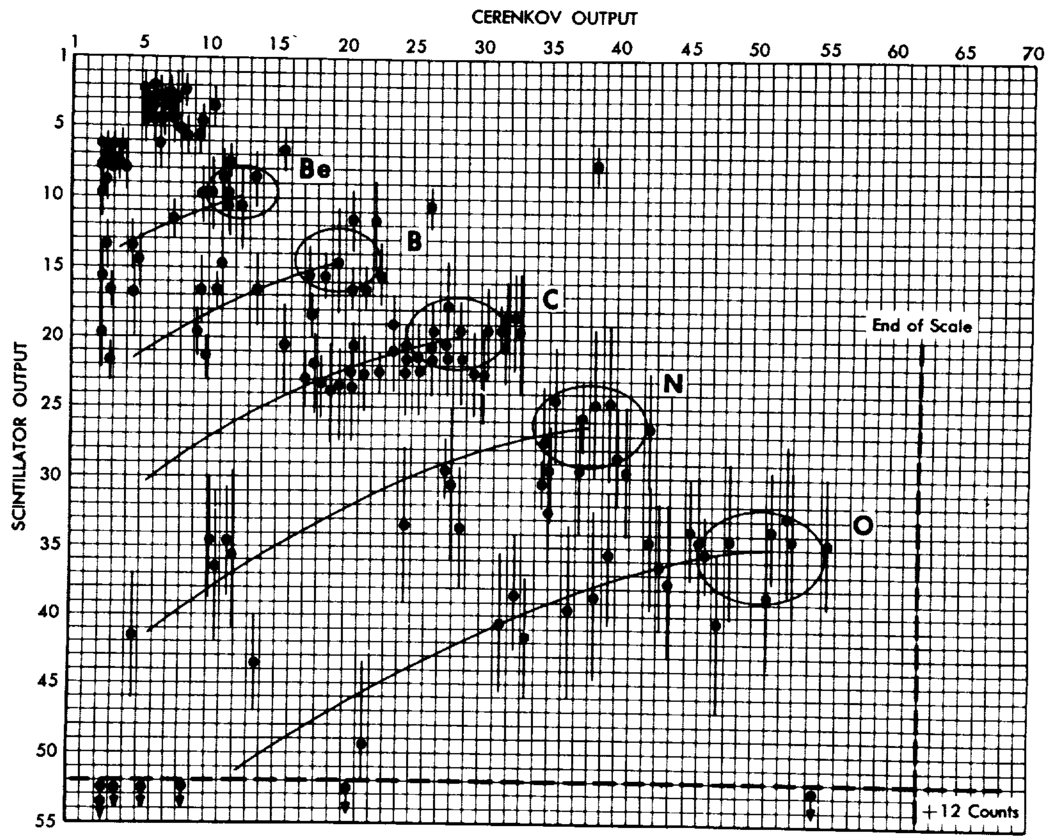

Figure 4—Plot of Cerenkov pulse height versus ionization loss in the three-element telescope of Figure 1. The end points of the individual lines represent the two measurements of ionization loss. A selection criterion that demands that the two measurements be within ±20 percent of each other has been applied. An appropriate correction for Landau fluctuations is then made. There is no evidence for background in the region beyond lithium, and the charge resolution is uniformly excellent.

the three flights that were due to single particles, with Z > 3, that traversed the detectors. The theoretically determined curves for the output of the detectors as a function of energy and charge are shown as solid lines. The normalization procedure is that discussed in the previous section. In Figure 4, which represents the results of the flight using a Cerenkov - double-scintillation counter, both scintillation outputs are shown, a single particle being assumed to traverse the telescope without interaction if the outputs of the two scintillators are each within ±20 percent of their mean value.

It should be pointed out that the intensities of protons and α particles were also measured on these flights. This was accomplished by switching the gain of the electronics so that for 15 minutes of every hour the gain was increased by a factor of 8 so as to record the smaller proton and α-particle outputs. We do not analyze the proton and α-particle results here in any detail but only use them for comparison with the heavier particle results on the same flights.

The charge and energy resolution of this type of detecting system for the heavier particles is evident from the figures without need for further elaboration. However, to convert the data contained in the figures to actual intensity and differential spectra values for the various charge components, a number of corrections, discussed in detail in the following section, are necessary.

DETERMINATION OF ABSOLUTE INTENSITIES OF VARIOUS NUCLEI

Since we have selected only counts that are clearly due to single particles traversing the detecting system, it is necessary to make a number of corrections to the raw data reported in the previous section. These corrections are not large and, furthermore, are reasonably well known. They are very similar to the corrections that were used to determine the absolute flux of protons and α particles in a concurrent series of balloon flights and were discussed in detail by McDonald (Reference 9) and McDonald and Webber (Reference 6).

For the heavier nuclei the data in Figures 2 through 4 must be corrected (1) for the nuclear interactions of the heavier particles in the detecting system itself, resulting in the absorption of these particles; and (2) for the effects of knock-on electrons produced by these particles as they pass through the detector. Finally, to obtain the absolute intensities at the top of the atmosphere, it is necessary to make a diffusion extrapolation of the corrected intensities at the flight altitudes to the top of the atmosphere.

1. *Correction for nuclear interactions in the detector:* Since the raw data include only clearly identifiable single particles passing through the telescope, they exclude those particles that interact as they pass through the telescope. On the reasonable assumption that at least two products occur for each interaction, these events should be recorded by the guard system (or, with the second detector, the pulse height after the interaction is significantly different than that before). Subsidiary experiments (Reference 6) suggest the guard system has in fact an efficiency of ≈ 1 for such events. The correction for the number of counts lost because of nuclear interactions can then be made, the interaction mean free paths of the various components in the telescope being known. This correction is given in Table 2.

Table 2

Corrections to Raw Balloon Flight Data.

Corrections (percent)		Flight 6	Flight 7	Flight A
Correction for nuclear interactions in telescope*	λ_L' (glass) = 45 gm/cm^2	-28 ± 5	-28 ± 5	-19 ± 5
	λ_M' (glass) = 40 gm/cm^2	-33 ± 6	-33 ± 5	-24 ± 6
	λ_H' (glass) = 30 gm/cm^2	-43 ± 8	-43 ± 8	-30 ± 6
Knock-on electron correction for E > 0.5 Bev/nucleon	L	-2 ± 1	-2 ± 1	None
	M	-5 ± 3	-5 ± 3	
	H	-12 ± 8	-12 ± 8	
Correction to the top of the atmosphere* (diffusion extrapolation)	L	-0 ± 5	-0 ± 5	-0 ± 5
	M	-24 ± 5	-19 ± 4	-18 ± 4
	H	-30 ± 6	-25 ± 5	-24 ± 5

*Interaction mean free paths in glass and air, and fragmentation parameters, after Waddington (Reference 13).

2. *Correction for knock-on electrons produced in the detector:* It is possible for particles, as they pass through the telescope, to produce knock-on electrons having sufficient energy to set off at least one of the guard counters. Such events will be rejected, even though a single particle traverses the telescope without interaction. This correction depends on the charge and energy of the particle in question. Detailed calculations of this effect have been made to interpret previous experiments on protons and α particles (References 9 and 14). This correction, as applied to the heavier nuclei in this experiment, is shown in Table 2. Note that no correction for this effect is necessary in the case of the Cerenkov - double-scintillation counter array.

The absolute flux values obtained after the above corrections are extrapolated to the top of the atmosphere in the conventional manner with the diffusion equations as introduced by Kaplon, Noon, and Racete (Reference 15). The interaction mean free paths and fragmentation probabilities used are those determined by Waddington (Reference 13) in his survey of available data on the subject, and it has been assumed that they do not vary appreciably over this range of energies. Energy loss has not been introduced directly into the diffusion equations; instead, the energy intervals appropriate to the flight altitude ≈ 6 gm/cm^2 for each charge group have been corrected for energy loss to give the equivalent intervals at the top of the atmosphere. This will give a small but insignificant bias due to wrong assessment of energies.

Table 3 summarizes the results of the three flights corrected to the top of the atmosphere. Figure 5 shows the differential spectra of M nuclei that were measured on each of the flights. For comparison the differential spectra of α particles measured on the same flights and divided by a constant factor of 15 are shown. Finally, in Figures 6 and 7 the L/M ratio and α/M ratio are shown as a function of energy for the average of the three flights and for each flight separately.

Table 3

Absolute Intensities of the Various Components at the Top of the Atmosphere.

Flight Number and Date	Energy Interval at Top of Atmosphere (Bev/nucleon)	α Particles / m^2-ster-sec	Light Nuclei* / m^2-ster-sec	Medium Nuclei / m^2-ster-sec	L/M	Heavy Nuclei† / m^2-ster-sec
6: Mar. 20, 1956	>0.43	176 ± 6	4.3 ± 0.7	10.2 ± 0.9	0.42 ± 0.06	3.4 ± 0.6
	0.43 - 0.57	19.3 ± 1.3	1.1 ± 0.4	1.7 ± 0.4	0.65 ± 0.19	
	0.57 - 1.06	45.5 ± 3	1.2 ± 0.4	2.6 ± 0.4	0.46 ± 0.15	
	1.06 - 1.55	24.3 ± 2	0.45 ± 0.2	1.8 ± 0.4	0.25 ± 0.09	
	>1.55	86 ± 3	2.1 ± 0.5	4.4 ± 0.6	0.48 ± 0.09	
7: Aug. 17, 1956	>0.41	225 ± 10	4.5 ± 0.9	15.3 ± 1.3	0.29 ± 0.08	3.8 ± 0.8
	0.41 - 0.55	23 ± 3	0.7 ± 0.3	2.3 ± 0.5	0.31 ± 0.12	
	0.55 - 1.04	67 ± 5	1.8 ± 0.6	4.4 ± 0.7	0.41 ± 0.12	
	1.04 - 1.53	36 ± 4	0.8 ± 0.4	2.4 ± 0.5	0.33 ± 0.14	
	>1.53	88 ± 5	1.3 ± 0.6	6.4 ± 0.9	0.2 ± 0.06	
A: Aug. 1, 1960	>0.55	105 ± 6	2.5 ± 0.5	7.2 ± 0.6	0.35 ± 0.07	1.8 ± 0.4
	0.55 - 1.04	20 ± 2	0.8 ± 0.3	1.8 ± 0.4	0.45 ± 0.12	
	1.04 - 1.53	14 ± 2	0.2 ± 0.1	1.1 ± 0.4	0.18 ± 0.12	
	>1.53	12 ± 1	1.7 ± 0.4	4.1 ± 0.5	0.41 ± 0.10	

*Li 1/4L.
†Z $\geq$ 10.

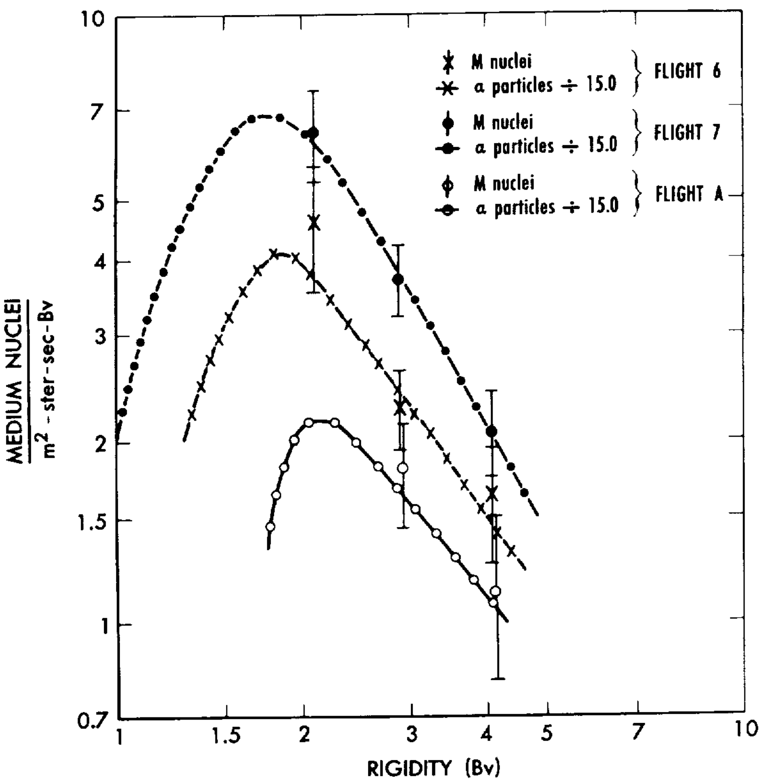

Figure 5—Measured differential rigidity spectrum of M nuclei. The appropriate α-particle data divided by 15 are also shown for comparison.

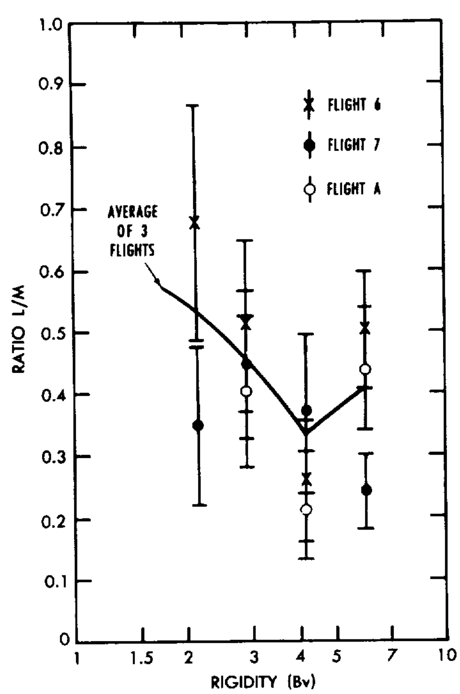

Figure 6—The measured L/M radio as a function of rigidity. In the region of these studies, $1.5 \leq R \leq 6$, the results are consistent with a constant L/M over the entire rigidity interval, although there is some evidence it may be increasing at smaller values of R.

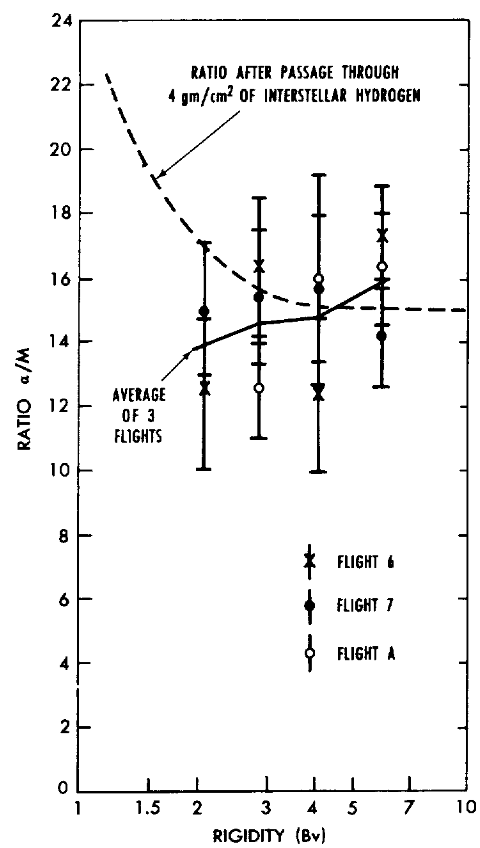

Figure 7—The measured α/M ratio as a function of rigidity. The dotted line indicates the expected ratio after passage through 4 gm/cm^2 interstellar hydrogen, assuming that originally α and M nuclei have the same form of rigidity spectrum.

DISCUSSION OF EXPERIMENTAL RESULTS

We shall divide our discussion of the measurements reported in the previous section into three separate aspects:

1. *The simple L/M ratio:* The average L/M ratio at the top of the atmosphere for the three flights is 0.36 ± 0.06 for particles with energy greater than 1.55 Bev/nucleon or 0.38 ± 0.05 for particles with energy greater than 0.41 Bev/nucleon. These values are in generally good agreement with those that have been obtained by emulsion techniques. In his survey of all previous determinations using these methods, Waddington (Reference 13) derives a mean L/M ratio of 0.29 ± 0.03 for particles with energy greater than 1.5 Bev/nucleon. The more recent L/M determinations of Van Heerden and Judek (Reference 16), 0.35 ± 0.04, and O'Dell et al. (Reference 17), 0.25 ± 0.05, for particles with energies greater than 1.5 Bev/nucleon—or Aizu et al. (References 3 and 4), 0.41 ± 0.06, and Fichtel (Reference 1), 0.40 ± 0.08, for particles with energies greater than 0.4 Bev/nucleon—give a clear indication that there is no longer any substantial uncertainty in this ratio, whether it is measured by emulsion techniques or by counter techniques.

A clear difficulty arises in using this ratio to attempt to calculate the amount of interstellar material traversed by the primary radiation however. Making the usual assumption that the L nuclei are absent in the source region and the additional, and artificial, assumption that all particles traverse the same amount of interstellar material (one-dimensional diffusion), Hayakawa et al. (Reference 18) have concluded that an L/M ratio of 0.3 implies that the most probable amount of matter traversed was 3 ± 0.5 gm/cm^2. Using more recent values for the fragmentation parameters of the heavier nuclei in hydrogen, Fichtel (Reference 19) arrived at a value of 5 ± 2 gm/cm^2 for the same L/M ratio. The differences in these values and the uncertainties in the values themselves represent the degree of our uncertainty about the fragmentation parameters for heavy-nuclei collisions with interstellar hydrogen.

A number of other possibilities exist for models of the diffusion of the primary radiation through interstellar space—for example, steady-state three-dimensional diffusion from a point source in an infinite medium of constant density; the same except with uniform injection throughout the volume and either slow leakage or perfect reflection at the boundary (References 20 and 21). In these models the L/M ratio is a function of energy (even without considering the effects of Fermi acceleration or ionization loss in interstellar space). We shall discuss this fact further in the following sections. If the cosmic rays are restricted to lines of force, which may be more regular in the galaxy than is sometimes supposed, then the usual diffusion treatments must be modified. The direct injection of L nuclei by spallation in stellar atmospheres where heavier cosmic rays have already been accelerated may also influence the interpretation of the L/M ratio.

2. *The solar modulation effects on the heavier nuclei:* The work of McDonald (Reference 9), McDonald and Webber (References 6 and 7), Webber (Reference 10), and Meyer (Reference 22) has established to quite a high degree of accuracy that the sunspot cycle changes or modulation of the proton and α-particle intensity are identical for particles of equivalent rigidity. Furthermore, the intensity of protons or α particles at the top of the atmosphere can be uniquely related to the counting rate of a sensitive neutron monitor near sea level at the same time. Since the heavier nuclei have

effectively the same charge to mass ratio as the α particles, we should expect the rigidity-dependent modulation to be effective for them also. Because of the approximately similar ratio of Z/A for α particles through oxygen, it is impossible to distinguish between rigidity-dependent modulation and modulations involving energy/nucleons without considering the proton data. However, since the proton and α-particle data have established a rigidity-dependent modulation, the interpretation of the modulation of light and medium nuclei is carried out using rigidity. While it would be more convincing to plot L and M with proton data, the α-particle flux values are used since greater overlap between the two sets of data is obtained during a given flight. Observations by Frier et al. (Reference 23), Fichtel (Reference 1), Van Heerden and Judek (Reference 16), Yagoda (Reference 24), and Biswas et al. (Reference 25) during the recent sunspot maximum period have clearly indicated that the intensity of heavier nuclei varies considerably throughout the sunspot cycle and is much lower at this time than at sunspot minimum. This variation has been directly related to the concurrent variations of protons and α particles by the above authors.

The results included here cover an extended period from a very high cosmic-ray intensity indicative of sunspot minimum to a low cosmic-ray intensity indicative of sunspot maximum. Perhaps the best way to illustrate the behavior of the heavier nuclei during this period is to plot the intensity of the most abundant of these nuclei, the M nuclei, against the counting rate of a sensitive neutron monitor. Such a plot is shown in Figure 8. Since deviations from a rigidity-dependent modulation would be expected to be most pronounced at lower energies, we have included only measurements that extend down to ≈ 500 Mev/nucleon or less. The dashed curve in Figure 8 represents the intensity of α particles > 400 Mev/nucleon as a function of the Mt. Washington neutron monitor rate as deduced from the α-particle measurements on these three flights, as well as a more extended analysis by McDonald and Webber (Reference 7) of proton and α-particle data over twenty flights during the sunspot cycle. The α-particle intensities are divided by a constant factor of 15 ± 1. There is no suggestion from the figure that anything but a constant factor suffices to normalize the proton and α-particle and M-nuclei data over the sunspot cycle despite the fact that the integral intensity of M nuclei varies by a factor of greater than 2 during this time.

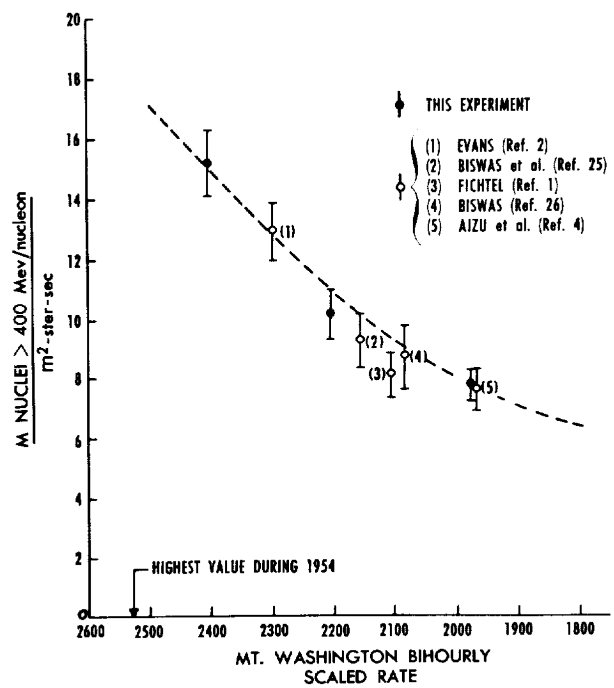

Figure 8—The variation of integral medium nuclei intensities above 400 Mev/nucleon during the period 1956-1959 as measured by various observers. Intensities are shown as a function of the Mt. Washington neutron counting rate at the time of measurements. The dotted curve represents McDonald and Webber's (Reference 7) proton and α-particle results divided by 72 and 12 respectively.

Examination of the differential spectra of α particles and M nuclei derived from the three flights and shown in Figure 5 also suggests that there are no systematic changes in the relative differential spectra of these charge groups during the solar cycle.

The above arguments may be extended with less accuracy to include the L and H nuclei as well. No systematic changes in the L/M or H/M ratios are noted during the course of the three flights (see Table 3 and Figure 6).

The results on the heavier nuclei are thus consistent with the modulation of the α particles. When taken with the proton - α-particle modulation characteristics already pointed out, they provide an additional (although statistically much less significant) support for the earlier conclusion that the solar modulation is identical for particles of the same rigidity. In particular the experimental results appear to be accurate enough to rule out simple types of electric field as the cause of the modulation of the primary radiation (e.g., Reference 27).

To detect possible deviations from the simple rigidity-dependent picture to which the experimental evidence seems to be leading will require a definite advance in technique and a substantial increase in counting rates. In addition particular attention should be paid to the changes in intensity of the lowest rigidity particles (those below about 1.5 Bv), for it is this rigidity region in which the greatest deviations between the charge components might be expected.

3. *Spectral and charge characteristics of the unmodulated galactic heavier primary radiation*: To assess these characteristics of the primary spectrum properly, it is necessary to be assured that we are indeed measuring the true galactic spectrum, unmodulated by any solar influences. Certainly at times other than those near sunspot minimum the solar modulation effects will not be small, particularly at low energies. It is clear from the discussion in the previous section that the features of the solar modulation have not been accurately enough delineated, so that considerable uncertainty is introduced in interpreting measurements made near sunspot maximum that have been corrected for these effects. At sunspot minimum it is likely that the solar modulation is small even for the lowest rigidity particles (Reference 10). For this reason the results of flight 7 of this series are of particular interest.

The differential spectrum of M nuclei obtained on this flight and shown in Figure 5 is of value even though the measurements do not extend to rigidities below the peak in the spectrum. The constant factor of ≈ 15, which appears to relate this spectrum to the α particle (and proton) spectrum at a given rigidity that were measured at the same time, suggests that the galactic influences on the shape of the spectra are similar to those for α particles and protons.

To investigate this feature in another way, we have plotted the α/M ratio for the three flights in Figure 7. If we suppose that the modulation effects are indeed rigidity-dependent, then the results of the other two flights may be utilized with a proper degree of caution in this analysis.

The results of all of the flights are consistent with a constant α/M ratio. In fact this ratio decreases slightly with decreasing rigidity, although this decrease cannot be regarded as statistically significant. As a particular example of a set of circumstances in which the α/M ratio should be an increasing function of rigidity towards lower rigidities, let us consider cosmic rays emitted from a source region with each charge having the same differential rigidity spectrum. If we assume no further acceleration in interstellar space, the subsequent spectral shape will be determined principally by ionization loss in the interstellar material, and the heavier nuclei at a given rigidity will lose energy at a greater rate. As a consequence, differences will appear in the spectra of the low-energy heavier nuclei; and, in particular, the peaks of the differential spectra will occur at higher rigidities for particles of increasing charge (References 28 and 10).

With these assumptions it can be seen from Figure 7 that, despite the crudity of the experimental results reported here, an upper limit of ≈ 4 gm/cm^2 of interstellar material is obtained. Measurements of this type do not, of course, uniquely determine the amount of material traversed. The possibility exists that the source regions could preferentially emit the low-rigidity heavier nuclei (e.g., Reference 29) so as to precisely offset the increased energy loss through ionization in the interstellar medium. Another possibility is that only processes in interstellar space are of major importance in shaping the spectra, and the competition between an acceleration process (e.g., the Fermi type) and ionization loss determines the shape of the spectra at low rigidities for the various charges. Then a critical rigidity would exist at which the rates of energy gain and energy loss by these two processes are equal. For nonrelativistic particles this rigidity can be shown to be equal to $K\,(A^2/Z)^{1/3}$, where K is a constant independent of the particle in question. In this picture we should also observe a systematic increase in the rigidity of the peak of the differential spectra for particles of increasing charge and, in particular, an α/M ratio that increases even more rapidly at low rigidities.

A wide variety of possibilities are therefore available for the interpretation of the results so far discussed, and it seems worthwhile to introduce the other experimental evidence relating to this matter. In Figure 6 we have shown the L/M ratio as a function of rigidity as determined on the three flights. Neither the average of the three flights nor flight 7, in particular, can be interpreted as implying anything but a constant L/M ratio of ≈ 0.4 between 2 and 6 Bv. The suggestion of an increasing L/M ratio with decreasing rigidity is not statistically significant. Thus we are led again to conclude that the galactic spectra of the various charge components are closely similar when plotted as a function of rigidity.

Additional, although more indirect, evidence comes from an examination of the H/M ratio or, what is equivalent in our arguments, the α/H ratio. Any changes in the relative intensities of the different components of the galactic radiation should be most clearly shown by comparing these two groups with greatly differing charge. Although in this experiment we do not actually measure the rigidity spectrum of the H nuclei, we do obtain the integral intensity of H nuclei $>$ 400 Mev/nucleon. From this the α/H ratio turns out to be 62 ± 12 for flight 7 alone, or 57 ± 5 for the average of all of the flights. At a cutoff energy of 1.5 Bev/nucleon, the α/H ratio as deduced from the summary of Waddington, which includes the best experimental determinations up to 1959, is 42 ± 4. From this comparison we see the indication of an increasing α/H ratio with decreasing rigidity; however, this will be better established only by actually measuring the spectra of the heavier nuclei with a single instrument.

From our results on the comparative differential rigidity spectra of the various charge components we can say that, if processes such as Fermi acceleration and ionization loss in interstellar space are unimportant, the diffusion models that predict that the amount of interstellar material traversed is constant with energy are most consistent with our results. A model in which all or most nuclei of low charge are fragments of heavy nuclei that are assumed to be the only ones emitted from the source region (References 29 and 30) would not be consistent with our results. In such a picture the H nuclei would be "older" than the others and would have traversed ≈ 2 times as much interstellar material. Since the amount of material traversed must be ≈ 10 gm/cm^2 at least to produce the required fragmentation into lighter particles, this should produce a difference in spectral shape greater than that implied by the measurements.

The general picture we have tried to present above, namely, the strong similarity of the differential spectra of the various charge groups, even to the point of making the effects energy loss in interstellar hydrogen on the borderline of detection, is consistent with the data of Fichtel (Reference 1). It agrees only in part with the work of Aizu et al. (References 3, 4, and 31) however. Apart from a general similarity of the spectra of the various charge groups, these authors find an L/M ratio that appears to increase with decreasing energy and that accordingly is said to reflect an increased amount of matter traversed by the low-energy particles. In addition, they find an H/M ratio that appears to decrease with decreasing energy.

On the other hand, Tamai (Reference 5) finds a systematic difference in the differential spectra of the various charge groups. The position of the maximum in the different spectra tends toward higher energy with increasing charge—an effect suggesting that ionization loss in interstellar space is an important feature. Tamai also observes an L/M ratio of ≈ 1 for particles with energy < 700 Mev/nucleon, which would imply however that the elongation of the path length or the energy dependence of the fragmentation parameters dominates for the L nuclei.

From the above results it is clear that a consistent picture does not exist between various experimenters with regard to the actual shape of the low-energy portion of the galactic spectrum for the various charge groups. Two of the most serious causes for the discrepancies that now exist would seem to be: (1) *The influence of the solar modulation effects:* The three emulsion experiments reported above were all made at a time near sunspot maximum, and sometimes when the effects of Forbush decreases were important. Our present knowledge of the solar modulation effects on the heavier nuclei makes the problem of defining the actual galactic spectrum from these results one of increased difficulty. (2) *The lack of results of high statistical accuracy:* The differential spectra determined to date for the heavier charges have been based on 100 to 200 counts or less for each charge group. To define usefully the differences in spectra of the various charge groups, if they exist, requires counting rates of at least one order of magnitude greater.

As a final comparison of our results with previous emulsion results, the actual charge distributions obtained are shown in Table 4, together with the summary of Waddington (Reference 13) for energies > 1.5 Bev/nucleon and the recent results of other workers. The charge composition determined by counter techniques agrees quite well with the average of the emulsion results, with perhaps a greater abundance of C and O as recorded in our experiments. All results show a sufficiently wide scatter, however, to indicate that a measuring uncertainty of at least 1 charge unit in the range $4 \leq Z \leq 8$ must occur in some of the experiments.

Table 4

Comparison of Charge Distributions Obtained at the Top of the Atmosphere.

Charge	Counts*	Charge Distribution (percent)						
		(†)	Waddington (Ref. 13)	Aizu et al. (Refs. 3 and 4)	Tamai (Ref. 5)	Fichtel (Ref. 1)	Biswas et al. (Ref. 25)	O'Dell et al. (Ref. 17)
Li	-	(6-8)	3.9	8.8	10.0	7.4	(2.1)	5.3
Be	46	6.7	1.7	6.0	14.0	5.7	(3.0)	2.3
B	70	10.1	11.6	10.9	15.7	9.0	17.8	7.4
C	197	28.6	26.0	29.2	18.8	27.1	20.9	30.1
N	92	13.3	12.4	14.8	7.8	15.3	16.6	9.7
O	123	17.9	17.9	14.4	7.3	14.4	8.9	19.4
Z >10	114	16.6	23.9	18.0	20.5	21.7	31.4	23.4

*Total of three flights.
†Percentage of all particles with $Z > 3$ in this experiment.

CONCLUSIONS

From the results we conclude the following:

1. Cerenkov-scintillation detector combinations can be used to measure the rigidity and charge spectra of the heavier nuclei. The energy and charge resolution is comparable with that obtained by the latest emulsion techniques. Use of advanced counter systems can extend the measurements to the lowest energies without serious background corrections. The rapid processing of data and the high counting rate of the counter systems can be used to advantage in investigating characteristics of the spectra related to the origin of the radiation and also to the solar modulation effects.

2. The solar modulation of intensity appears to be identical for all positively charged particles of the same rigidity. We have specifically extended this conclusion to include particles heavier than α particles in the three flights reported in this paper.

3. The measurements near sunspot minimum establish a high degree of similarity in the differential spectra of the various charge components only when the spectra are expressed in terms of the rigidity of the particles. This similarity is sufficient to make it unlikely that the particles have traveled through more than 4 gm/cm² of interstellar hydrogen. It appears, furthermore, that the peaks in the differential spectra of the heavier particles that are observed at times near sunspot minimum cannot be due to some residual solar modulation effect or to the effects of ionization loss alone, or ionization loss competing with Fermi acceleration processes in interstellar space. If the form of the differential spectra and their similar rigidity dependence are to be taken seriously, they may reflect the action of large-scale regular fields either near the source region itself or in interstellar space.

4. The relative and absolute intensities of the various charges as measured in this experiment are comparable with those obtained using emulsions. In particular an L/M ratio of 0.36 ± 0.05 essentially independent of rigidity from 2 to 6 Bv is obtained. Such a ratio is consistent with the passage of the primary radiation through 4 to 6 gm/cm² of interstellar hydrogen, this value also being independent of rigidity. The amount of hydrogen and, indeed, the method of "passage" through interstellar space depend so critically on actual interstellar conditions as well as on the distribution of sources, however, that such a value is regarded as having definitive meaning only when combined with simultaneous measurements of a number of other characteristics of the heavier nuclei and properties of the cosmic radiation in general.

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